Beam Dynamics Studies for RIA at Michigan State University (MSU)
(R&D Category: Beam Dynamics)

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1. Introduction

Since 1999, beam dynamics studies have been performed as part of an effort to establish a comprehensive RIA design at Michigan State University (MSU). These studies include: simulation of multi-charge-state beam acceleration and focusing in the three segments of RIA driver linac [1], analysis of transverse misalignment and rf errors on machine performance [2,3], design of the charge-stripping chicanes [4], and full six-dimensional beam simulations from the ECR to the ISOL/Fragmentation targets [5,6]. Other beam dynamics issues investigated were the triple-spoke cavity option [7] and the impact of the 2nd order parametric coupling resonance [8]. These studies provide essential support of the on-going SRF R&D program at MSU and of the development of simulation tools suitable for RIA.

2. RIA Driver Linac Lattice

Figure 1 shows the MSU RIA facility layout. The driver linac consists of three segments of SRF structures separated by two charge-stripping chicanes to accelerate all ions to energies ≥ 400 MeV/u with a beam power of 100 to 400 kW. For heavier ions, simultaneous acceleration of several charge states will be used to minimize the required accelerating voltage.

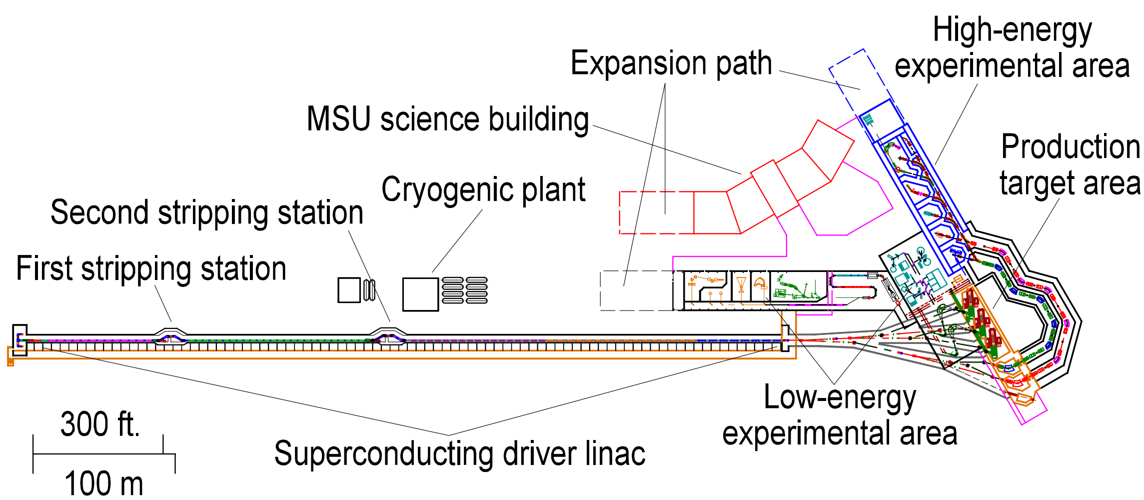

Figure 1: Layout of the RIA facility proposed by MSU.

Segment I of the RIA driver linac uses low-β, λ/4 SRF cavities with a frequency of 80.5 MHz and an aperture of 30 mm. Strong transverse focusing is provided using superconducting (SC) solenoids within the cryostats to control beam size and avoid beam loss. There are two SRF cavities between each pair of SC solenoids. Due to adiabatic damping, the 90° transverse phase advance per cell in the first two cryomodules can be gradually reduced to about 25° providing solenoid fields of less than 9 Tesla.

In Segment II, the transverse focusing is accomplished with 52 superconducting solenoids. The SRF cavities are low-β, λ/2 cavities with a frequency of 322 MHz and an aperture of 30 mm. There are four SRF cavities between each pair of SC solenoids inside each cryomodule. The maximum required solenoid field is about 8 Tesla with a transverse phase advance per cell of ~ 85°.

The transverse focusing in Segment III is accomplished with room-temperature quadrupoles positioned between the cryomodules. The SRF cavities are high-β, 6-cell elliptical cavities with a frequency of 805 MHz and an aperture of 77 mm. Each cryomodule contains four elliptical cavities.

Beam dynamics studies demonstrate that the RIA driver linac has adequate transverse and longitudinal acceptance. Figure 2 shows the beam envelopes and lattice apertures for the three segments of driver linac. Figure 3 provides the longitudinal emittance and acceptance at the beginning of three segments of driver linac.

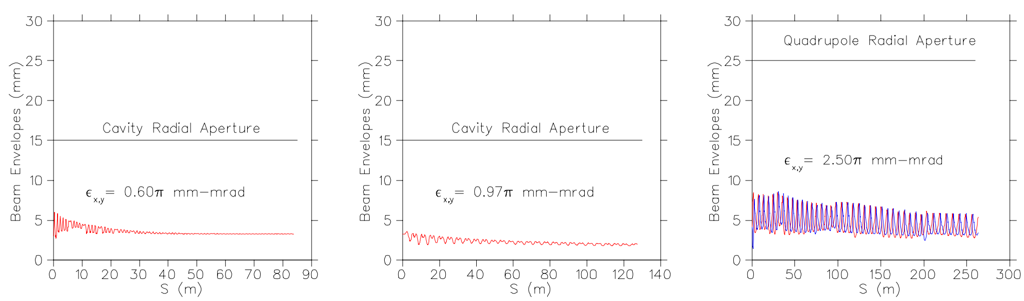

Figure 2: Beam envelopes and lattice apertures for Segment I (left), Segment II (middle), and Segment III of RIA driver linac.

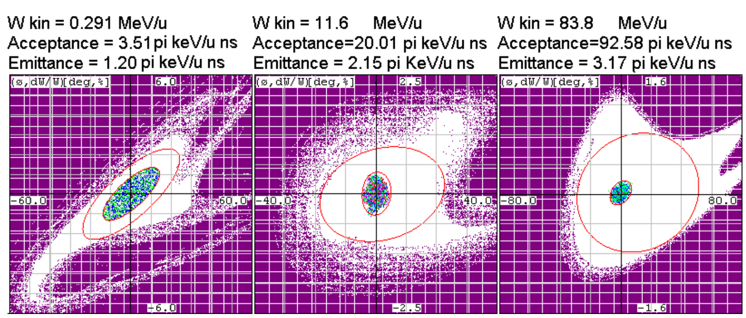

Figure 3: Beam emittances and linac acceptances at the beginning of Segment I (left), Segment II (middle), and Segment III (right) of the RIA driver linac.

3. Driver Linac Transverse Misalignment and RF Errors

Sensitivity to misalignment of the focusing elements and SRF cavities of the driver linac was investigated. All accelerating structures and focusing elements were misaligned assuming a Gaussian distribution (±2σ). The superconducting solenoids in Segments I and II, and the quadrupoles in Segment III were found to be more sensitive to the misalignment errors than the SRF cavities.

The alignment correction simulations assumed beam position monitors (BPMs) were located in the warm region between cryomodules. In Segment I and II, two solenoids in each cryomodule were assumed to have dipole windings to provide horizontal and vertical orbit correction. In Segment III, horizontal and vertical dipole magnets in the warm region were used for orbit corrections. A least-square fitting algorithm was used to minimize orbit distortions at all BPMs by adjustment of the horizontal and vertical correctors. Three-dimensional beam simulations for multi-charge beam were performed to evaluate the impact on the lattice performance, orbit distortion and emittance growth. With the misalignment tolerances listed in Table 1, within 90% confidence, the maximum orbit distortions are limited to ± 5 mm with a transverse beam emittance growth of 10 – 25% in all three segments. No beam loss was observed due to misalignment errors.

Table 1: RIA alignment tolerances.

RIA Driver Linac	SRF Cavity Misalignments and RF errors				Focusing elements misalignments	
	$\sigma_{x,y}$ [mm]	σ_{zr} [mrad]	Phase [deg]	Amplitude [%]	$\sigma_{x,y}$ [mm]	σ_{zr} [mrad]
Segment I	1.0	-	0.5	0.5	0.25	-
Segment II	1.0	-	0.5	0.5	0.5	-
Segment III	1.0	-	0.5	0.5	1.0	5.0

The random rf errors listed in Table 1 for all SRF cavities in the RIA driver linac lattice were then combined with the misalignment errors, and multi-seed simulations performed for the multi-charge state beams. Only the longitudinal rms emittance growth was found to have an observable change, indicating week coupling between the transverse and longitudinal motion. No beam loss was observed.

4. Triple-Spoke Cavity Option

The baseline RIA driver linac design uses 805 MHz 6-cell elliptical cavities to accelerate beam from the 2nd charge-stripping chicane at ~85 MeV/u to final energies of ≥ 400 MeV/u. An option of using 322 MHz triple-spoke cavities in lieu of the 805 MHz 6-cell elliptical cavities was proposed in 2002 [9]. Figure 4 shows section views of both the 6-cell elliptical and triple-spoke cavities.

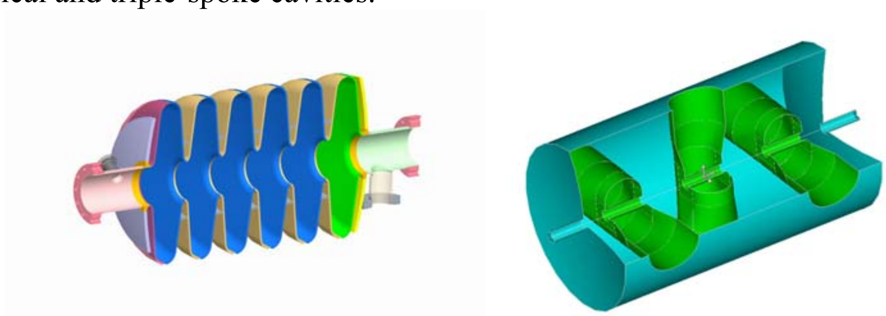

Figure 4: 6-cell elliptical (left) and triple-spoke cavities (right).

Accelerating and focusing lattices were established for these two cavity types and beam dynamics studies performed to compare the two options for Segment III of RIA driver linac. The results show that both the 805 MHz 6-cell elliptical and 322 MHz triple-spoke cavities could in principle provide the necessary acceleration. Due to its lower frequency and therefore longer effective accelerating gap, fewer cavities are needed for the 322 MHz triple-spoke cavity option. However, the triple-spoke cavity will have a much smaller aperture, and as a result, requires a more expensive superconducting solenoid-focusing lattice. No triple-spoke cavity exists and R&D would be required to determine its performance. The 805 MHz 6-cell elliptical cavities have a much larger aperture allowing a more cost effective quadrupole focusing lattice and have a more than adequate transverse and longitudinal acceptance. All three elliptical cavities have been successfully tested in 2002.

5. Parametric Resonance Studies

In the MSU design option, all cryomodules in Segment III of RIA driver linac will have four 805 MHz 6-cell elliptical cavities. Beam dynamics studies were performed to evaluate the sensitivity to instabilities induced by transverse to longitudinal coupling. No emittance growth was observed for the proposed four-cavity per cryomodule design [10].

6. Charge-Stripping Chicanes

Charge-stripping sections are necessary truncate the charge distribution and to match the multi-charge-state ion beams to the following linac segment. The proposed optical system has 4 identical cells with 4-fold symmetry. Each cell consists of a pair of reverse bending dipoles of –7.5° and +37.5°. The dispersion function symmetry results in an isopath condition for the multi-charge-state ion beams. The system has excellent 2nd order optical properties due to its high symmetry. No 2nd order geometric aberrations exist and there are only four chromatic terms that are completely cancelled by four correction sextupoles per cell. Only small perturbations from 3rd and higher order aberrations were observed.

The layout of the 1st charge-stripping chicane is given in Figure 5. A 1st order achromatic section was added in front of the charge-stripping target that shifts the beam axis by 5.3 cm to limit contamination of the SRF cavities in the preceding linac from the stripping process. A single λ/4 cavity with a frequency of 80.5 MHz and βopt of 0.085 will be used as the rf buncher. The transverse phase space for U^{238} at the beginning and end of the 1st charge-stripping chicane is shown in Figure 6. The longitudinal bunch length is maintained within ± 5° at the end of the 1st charge-stripping chicane, and only a 10% longitudinal emittance increase was observed. No significant transverse beam emittance growth was observed.

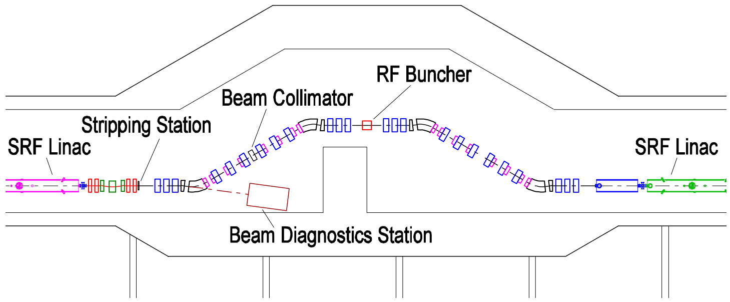

Figure 5. Layout of the 1st charge-stripping chicane for RIA driver linac.

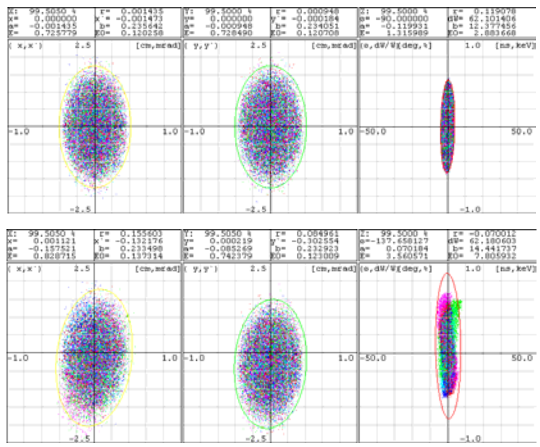

Figure 6. Horizontal (left), vertical (middle) and longitudinal phase spaces for U^{238} beam at the beginning (top) and end (bottom) of the 1st charge-stripping chicane.

The layout of the 2nd charge-stripping chicane is similar to the first. Four $\lambda/2$ cavities with a frequency of 322 MHz and βopt of 0.285 will be used as the rf buncher. No significant transverse beam emittance growth was observed. The longitudinal bunch length is maintained within ± 10° at the end of the 2nd charge-stripping chicane. No longitudinal emittance increase was observed.

7. Summary

The results of the beam dynamics studies show that the 10th sub-harmonic (80.5 MHz) RIA driver linac option has the adequate transverse and longitudinal acceptances. The misalignment and rf jitter specifications are reasonable and the proposed correction scheme works well. The coupling between the longitudinal and transverse motion is not strong. Although limited transverse and longitudinal emittance growths for multi-charge beam were observed due to the misalignment and rf errors, the impact on the RIA driver linac beam operation should be minimal.

8. References

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